



January 2007

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Hermann W. Pfefferkorn

University of Pennsylvania, hpfeffer@sas.upenn.edu

Jun Wang

Chinese Academy of Sciences

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Pfefferkorn, H. W., & Wang, J. (2007). Early Permian coal-forming floras preserved as compressions from the Wuda District (Inner Mongolia, China). Retrieved from http://repository.upenn.edu/ees_papers/51

Postprint version. Published in *International Journal of Coal Geology*, Volume 69, Issue 1-2, 2007, pages 90-102.

Publisher URL: <http://dx.doi.org/10.1016/j.coal.2006.04.012>

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Keywords

Coal-forming flora, Compression flora, Early Permian, Inner Mongolia, China

Comments

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Early Permian coal-forming floras preserved as compressions from the Wuda District (Inner Mongolia, China)

Hermann W. Pfefferkorn ^{a,*}, Jun Wang ^b

^aDepartment of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA 19104-6316, USA

^bNanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China

* Corresponding author. Tel.: +1 215 898 5156; fax: +1 215 898 0964.

E-mail address: hpfeffer@sas.upenn.edu (H.W. Pfefferkorn).

Abstract

Four different compression/impression floras are preserved in only 4.32 m of the geologic section in the Early Permian Shanxi Formation of the Wuda District of Inner Mongolia, northwestern China. These floras represent four different plant communities and landscapes that followed each other in time. The oldest flora was rooted in sandy clay and initiated peat accumulation that led to the formation of the lower coal seam. This seam is 230-cm thick and overlain by a 66-cm thick volcanic tuff that preserves a second different flora that grew on the peat at the time of the ash-fall. Standing stems and large plant parts are present. The upper part of the tuff is rooted by a single species of lycopsid (the third flora) again initiating peat accumulation. On top of this second seam of 120 cm thickness rests a roof-shale, deposited as mud in a shallow lake, the formation of which was responsible for the cessation of peat deposition. This fourth flora represents the plants growing around the lake on clastic substrate. Four different environments followed each other in this locality over a geologically short time span and each time conditions prevailed to preserve plant macrofossils. Three of these floras represent peat-forming plant communities of essentially the same time interval. This demonstrates the great variability of vegetation and landscapes in the tropical Cathaysian realm of the Late Paleozoic.

Keywords: Coal-forming flora; Compression flora; Early Permian; Inner Mongolia; China

1. Introduction

The Late Paleozoic was the only other time interval in Earth history we can directly compare with our own because both experienced a cold interval of Earth climate with glacial and interglacial stages while Earth was covered by large plants forming dense vegetation in all suitable environments (Gastaldo et al., 1996; Pfefferkorn et al., 2000). Therefore, it is of interest to study vegetation and landscape changes in the Late Paleozoic to compare patterns of change during the two time intervals. This paper reports the discovery of four floras/landscapes that followed each other over a short time, being preserved in less than 5 m of stratigraphic section that does not contain any significant hiatus. Three of these four floras are peat/coal-forming even though they are preserved as compression/impression floras. These three floras occur in situ (autochthonous) while the fourth one is parautochthonous. Thus, all four floras allow the reconstruction of flora and landscape at three times during the formation of a coal seam and directly following the cessation of peat accumulation. These macrofloras can serve also as a control when palynological work will be done.

Previous paleobotanical work on the area by Sun et al. (1996, 1998), Sun and Deng (1999), and Deng et al. (2000) gave an overview of Carboniferous and Permian floras in the northern Helan Mountains including the Wuda area, their general paleoecology, and presented new taxa (*Paratingiostachya*, *Caulopteris wudaensis*, and

Chansitheca wudaensis). Our taphonomic and paleoecologic interpretations of these specific floras give an indication of the large amount of information that can be uncovered by further research in this area. We report the discovery and present the early taphonomic and paleoecological investigations of a particular coal sequence and the surrounding strata.

The two coal seams and the associated clastic and volcanogenic rocks are exposed in a shallow strip mine with several tunnels that follow one or the other coal seam along strike. The section was measured and plant macrofossils collected from each bed in which they were recognizable. Sedimentologic and taphonomic observations were recorded and representative specimens collected as reference material. The specimens are housed in the paleobotanical collection of the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China (catalogue numbers PB 20755 to PB 20772). Plant fossil taxa are being mentioned here largely at the generic level because this paper is not the place for detailed taxonomic treatment of the flora that will occur elsewhere.

2. Geographic and geologic setting

The locality is situated at N 39°28'53", E 106°38'08" in the Wuda Coal District near the city of Wuda in the Inner Mongolia (Nei Mongol) Autonomous Region of North China (Fig. 1A). The Wuda District lies in the northwestern foothills of the Helan Shan, a

mountain chain occurring mostly and with its highest elevations (up to 3556 m) in the neighboring province of Ningxia (Fig. 1B). The locality has an elevation of around 1270 m. Weathering resistant rocks are very well exposed in this region due to the dry climate and the lack of any continuous soil or plant cover. Less resistant rocks like coal or shale are mostly covered by talus but are exposed in this district by the extensive, ongoing mining activities. The plant fossils described here occur below, between, and above the Number 6 and Number 7 coal seams, using local mining terminology. In this district, coal seams are numbered starting at the top of the section so that the oldest coal seam has the highest number. The coal seams are part of the Shanxi Formation that is of Early Permian age (Liu et al., 2000). The Shanxi Formation consists of coarse to fine clastic beds and coals that were deposited in fluvial, lacustrine, and paludal environments. Marine intercalations are missing (Bureau of Geology and Mineral Resources of Ningxia Hui Autonomous Region, 1990; Bureau of Geology and Mineral Resources of Nei Mongol (Inner Mongolia) Autonomous Region, 1991; Zhang et al., 1997). The beds studied can best be compared with strata present in the Ordos Basin. Geotectonically the area is part of the northwestern margin of the North China Plate. This plate formed a separate, large island in the tropical part of the Tethys Ocean (Fig. 2) throughout the Permian and collided with the Mongolian Plate in the latest Permian (Zhang, 1988; Wang et al., 1990; Ziegler et al., 1997). Paleobiogeographically, the flora belongs to the North China phytogeographical area (Shen, 1995; Wang and Shen, 1996; Shen et al., 1996; Wang et al., 1999). The Early Permian plants of this area are generally quite similar to those of central North China (Halle, 1927; Lee, 1963; He et al., 1995), but endemic species do occur in sufficient number so that a local designation, the *Caulopteris wudaensis*–*Paratingia* assemblage, was proposed (Sun and Deng, 2003).

3. Stratigraphic section

A description of the geologic section (Fig. 3) is necessary to put the explanation of taphonomic features into context. These in turn have to be considered because it is not common to find compression/impression (adpression) floras that represent a peat-forming flora (Gastaldo et al., 1995). The beds have an average strike of 140° and a dip of approximately 25°

NE. However, one can see in the continuous mining exposures that the beds are undulating and strike and dip are laterally variable. In addition, small-scale tectonic features, mostly NE dipping overthrusts with an offset of 1–2 m, can change the orientation of beds locally but do not disrupt the continuity of the beds. The structure of the larger syncline of which this section is a part does not have to be considered here.

Description of the section starting from top

>240 cm	Sandstone, coarse grained, light gray, cross-bedded, resistant to weathering, forming the top of the section and the backslope.
600 cm	Interlayered sandy shales, argillaceous sandstones, and ironstone layers
22 cm	Shale, fine grained, fissile, medium dark gray (N 4), with yellow weathering products on some bedding planes, <i>fossil flora 4</i>
120 cm	Coal seam #6, well bedded, two clastic partings (splits): Parting 2, 36 cm from bottom of seam, 4-cm thick Parting 1, 13 cm from bottom of seam, 1–3-cm thick
66 cm	Volcanic tuff layer, that consists of three major layers: Upper layer—about 20 cm, light gray (N 7), fine grained, rooted, <i>fossil flora 3</i> Middle layer — about 40 cm, white (N 9) crystal tuff, coarse grained, <i>fossil flora 2</i> Lower layer — about 6 cm, white, light gray with bluish layering, <i>fossil flora 2</i> Thickness of tuff layer is variable and rare channel features indicate that some local reworking and transport took place.
230 cm	Coal seam #7, well bedded, three clastic partings (splits): Parting 3, 40 cm from top of seam Parting 2, 130 cm from top of seam Parting 1, 180 cm from top of seam
14 cm	Underclay, sandy, medium dark gray (N 4), rooted, <i>fossil flora 1</i>
>30 m	Sandstone, shaly, variable weathering resistant
1 m	Sandstone, dolomitic, with weathering colors ranging from light brown (5 YR 5/6) to dark yellowish orange (10 YR 6/6) to moderate reddish orange (10 R 6/6); bottom of section

4. Fossil floras

4.1. Underclay, flora 1 (Fig. 4)

The underclay is quite sandy and forms the top of a medium-grained argillaceous sandstone. The underclay itself is richer in clay and organic matter and darker in color. Rooting occurs throughout the underclay and extends into the underlying sandstone in some places. Two kinds of roots were observed. Stigmarian rootlets are 5–11-mm wide, while other rootlets have diameters of 1.5–2 mm. *Stigmaria ficoides* axes are visible in numerous places (Fig. 4D). These

axes are about 10-cm wide, clearly in place with rootlets attached, and visible for distances of 1 to 2 m but in reality much longer.

The rooting can be classified according to the scheme proposed by Pfefferkorn and Fuchs (1991) as shallow horizontal rhizomes with lateral roots (G), with one generation of roots and the sedimentary structure of the beds largely preserved (II), roots preserved as flattened coaly films (b).

In some places nearly round depressions occur surrounded by slickensides marking the location of standing stems that locally influenced compaction. The stems themselves were removed in the mining operation. Fallen stems are also visible and three kinds can be distinguished. A featureless stem of 65 cm width is visible for more than 4 m. Large tree lycopsids are also present (Fig. 4E). They are more than 20 cm wide and mostly decorticated. Only one shows a leaf scar pattern that can be identified as *Lepidodendron* (sensu lato). Narrower axes of about 4-cm width are also common being preserved for length of 1 to more than 2m (Fig. 4C). They show some ill-defined striations but no other features. Most are straight but one has a curvature. In addition, the following plant fossils have been found in this bed: *Cordaite*s (Fig. 4A), *Sphenophyllum*, *Pecopteris* (Fig. 4A, B).

4.2. Lower and middle tuff layer, flora 2 (Fig. 5)

The volcanic tuff layer contains standing stems and large very well preserved leaves, stems and fructifications that occur parallel to bedding. In some places rooting penetrates from the upper tuff layer downward into this layer but it will be treated only in the description of the upper layer.

The upright stem bases are rooted in the underlying coal and cross the entire tuff layer wherever they are completely preserved. In most cases, they are deformed through later compaction of the tuff. The stems are visible only where the tuff has weathered slightly to just the right degree so that some outside material has fallen. For this or other reasons, they are not recognizable everywhere along the section.

In one area where standing stems were visible they occurred at the following distances from each other (in cm) 235, 110, 118, 200, 519, 310, and 210 with a mean distance of 283 cm. One stem has a diameter of 35 cm and surrounded by slickensides. The upper tuff layer is thickened in this place and protrudes downward into the site of the stem. Another stem

is 5–7 cm wide and appears to have a root mantle and a pronounced flaring at the base.

The plant macrofossils found in this layer include *Cordaite*s leaves (Fig. 5G) attached to branches, several leaves of *Paratingia* (Fig. 5D) more than 50 cm long in subparallel orientation, large parts of fronds of at least three species of *Pecopteris* (Fig. 5A, B, F), the stem genus *Caulopteris*, *Nemejcopteris feminaeformis* (Fig. 5E), a zygopterid fern, *Sphenophyllum* (Fig. 5C), *Pterophyllum* (Fig. 5H), and sphenopterid foliage.

4.3. Upper tuff layer, flora 3 (Fig. 6)

The upper tuff layer is characterized by *Stigmara* with rootlets (Fig. 6B–G) and the occurrence of an unidentified small stem (Fig. 6A). The stigmarian axes are only 2–3 cm wide (Fig. 6B) in contrast to those in the underclay that are consistently about 10 cm wide. The rootlets can fork once or twice. The very fine tuff preserves Stigmarian rootlets not only as collapsed bands as is normally the case in clastic sediments but also as three-dimensionally preserved filled cross sections that often show the vascular bundle and the tissue band that connects it to the outer cell layers (Fig. 6D–G).

The rooting can be classified according to the scheme proposed by Pfefferkorn and Fuchs (1991) as shallow horizontal (G) to vertical (H) rhizomes with lateral roots, with one generation of roots that are widely spaced (I), roots preserved as flattened coaly films (b) or three-dimensionally (c).

4.4. Roof-shale, flora 4 (Fig. 7)

The shale is very fine grained and finely bedded. Fossil plants are plentiful and matted. The flora consists of *Taeniopteris* (Fig. 7D), *Discinities* (Fig. 7D), *Yuania* (Fig. 7B), *Callipteris* sensu lato (Fig. 7A), *Cordaite*s, and a tree lycopsid distinct from those in the other beds (Fig. 7C). No rooting is visible. Plant fossils occur throughout the 22 cm of the bed. However, the overlying sandy shales do not contain any plant fossils indicating a distinct shift in sedimentary conditions and the landscape.

5. Taphonomic and paleoecological synthesis

Flora 1 (Fig. 8, bottom) found in the underclay is represented by underground and above ground parts of the plants (Fig. 4). The bed is thin and the rooting is present throughout

but not intensive indicating one generation of growth (Pfefferkorn and Fuchs, 1991) that coincided with the start of the peat formation. The presence of large tree lycopsids, with Stigmarian root systems with diameters of 10 cm for the *Stigmaria* itself, is consistent with and similar to pioneer vegetations in Euramerican systems that start peat formation (DiMichele and Phillips, 1994).

From underground systems (*Stigmaria* rhizophores) and stems it is clear that large tree lycopsids dominated this flora if not in number then at least in biomass. The large smooth stem points to the possible presence of *Cordaites*. The numerous narrow stems, including the curved one, and the slender roots most likely belonged to pteridosperms that grew in a manner similar to that described by Wnuk and Pfefferkorn (1984). Other components were tree ferns. Principally, it was a forest with two canopies (Fig. 8), a higher one formed by tree lycopsids and a lower one of tree ferns (Fig. 4A, B) and pteridosperms (Fig. 4C). It is predicted here that palynological investigations of the lowermost layer of the coal seam should show a similar composition changed only by the bias in the differences of palynomorph production in the different plant groups and the fact that some pteridosperm prepollen are larger than the standard cut-off for palynological investigations.

Flora 2 occurs in the lower and middle layer of the volcanic ash-fall tuff. It is represented by standing stems rooted in the underlying peat and large, rather complete and often articulated above-ground plant parts. Both observations point to the interpretation that this represents the flora that was living on the peat (Fig. 8, flora 2) when the volcanic ash-fall occurred. The thickness of the ash of 66 cm (in the compacted state) points to a strong and serious interruption of the landscape that killed the flora. Stems were surrounded and kept standing until they decayed. Large plant parts fell into the ash during the ash “rain” as they broke off under the weight of the ash.

The flora (Fig. 5) was composed of *Cordaites* trees which contributed stems and branches with leaves attached, several species of marattialean tree ferns of which we find mostly foliage but also stems, and several *Paratingia* leaves that come off the same stem. The reconstruction of the *Paratingia* plant as cycad-like used in Fig. 8 is similar to the interpretation of Simunek and Bek (2003) of the related *Noeggerathia* plant. The herbaceous vegetation is represented by *N. feminaeformis* and a

Sphenopteris species that probably represents a fern. Thus, the vegetation was dominated by *Cordaites* representing the tallest trees with tree ferns forming the intermediate layer and *Paratingia* the lower layer together with herbaceous forms.

This flora 2 represents a peat-forming flora but its composition is quite different from the one that started the peat formation (flora 1). Therefore, one can expect a high diversity of peat-forming floras throughout the coal seams.

The density of standing stems, where it can be observed, points to a rather close forest. With stems on average only 3 m apart trees were close to each other and biomass was high. The quantitative analysis of the spacing will be done after further extensive field research with a larger dataset.

In the lower and middle tuff layer it is noticeable that standing tree bases can be observed in certain areas but not in others. After field observations, it appears that a certain state of incipient weathering makes the stems visible. However, there is an alternative hypothesis that will be tested in future field studies. It is possible that some areas of the peat mire were covered by herbaceous vegetation and that therefore no standing stems will be found in some areas. Flora 3 occurs in the top layer of the ash-fall tuff (Fig. 8, flora 3) and is the recovery vegetation. It consists of underground parts of a single small lycopsid with a *Stigmaria* system (Fig. 6B–G). However, the diameter of the *Stigmaria* axes is small (2–3 cm) and the lateral rootlets are forking once or twice. The size is a distinct difference from the *Stigmaria* system observed in flora 1. This flora was the one that started peat formation of the overlying seam (Fig. 8, flora 3). The axis shown in Fig. 6A is of an uncertain systematic affinity and further collecting will be needed to clarify its position.

Flora 4 occurs in the roof-shale that shows no rooting or standing stems but excellent bedding. It appears to be a deposit of a quite and probably shallow lake. The plant parts are largely foliage and fructifications but stems, even large ones, are common in the lower part of the shale, but not directly over the coal (Fig. 7). This shale seems to preserve a flora that was swept in from the margin of the lake being thus parautochthonous and a representation of the flora that surrounded the lake (Fig. 8, flora 4). The composition of this flora is quite distinct even at the generic level with *Callipteris* s.l. (Fig. 7A), *Taeniopteris* (Fig. 7D right) and *Noeggerathiales* (Fig. 7B, and D left) being the

dominant forms. A tree lycopsid is present but is distinct from those occurring in the lower floras (Fig. 7C).

5. Discussion

Four fossil floras with a different composition occur in 4.32 m of the geologic section. Two of them, namely flora 1 and 3 include rooted structures and represent the floras that commenced peat formation of seam 7 and 6 respectively. Flora 2 is the flora that grew on the peat swamp of seam 7 in its final phase when the ash-fall occurred that terminated peat deposition for a while. Thus, these three floras are autochthonous and give us macroscopic information on the peat-forming floras of these three stages of the two coal seams.

Three of the four floras (floras 1, 3, and 4) contain or consist of tree lycopsids. However, each one has different taxa showing the ecological diversity of the group and also differences of the landscape that could support completely different taxa of the same group at different times.

The three peat-forming macrofloras give us a detailed insight into the composition of these floras that will be a good control for the interpretation of palynofloras from the same coals. The macrofloras contain information like the spacing of trees that would be unavailable from other methods.

Preservation of plant fossils in ash-fall or re-deposited volcanoclastic sediments is well known from many periods of Earth history (Spicer, 1991) and has been reported from the Permian of China (Hilton et al., 2001a,b; Wang et al., 2003). Similarities exist with the Permocarboneous floras found in volcanoclastic beds, including ash-fall tuffs, in Saxony (Barthel, 1968; Barthel and Rössler, 1995; Rössler and Barthel, 1998) both in terms of floral composition and mode of preservation.

Floral successions in landscapes have been described for modern and quaternary cases extensively (Delcourt and Delcourt, 1991). Peats have yielded information on the changes of vegetation in the mire through macrofossils (Hughes and DuMayne-Peaty, 2002) and the surrounding vegetation through palynomorphs. In Late Paleozoic strata, studies have demonstrated successions in coal seams either through permineralized macrofossils (Phillips et al., 1977; Phillips and DiMichele, 1998; Greb et al., 1999) or palynomorphs (Bartram, 1987; Eble, 2003). For clastic sequences that are

slightly older than the ones studied here, a succession from calamite to lycopsid-dominated vegetation was described by Li et al. (1991) from the neighboring province of Ningxia.

Thus, floral successions over short time intervals, from decades through thousands of years, are known from many environments but rarely preserved in the fossil record. The four floras we describe here were preserved as the landscape changed and each represents a different environment. Therefore, it is not surprising that the taxonomic composition of the four floras is also quite different from each other. It also indicates that the species involved lived somewhere in the larger area and could invade this particular site when conditions for growth were suitable. Thus, this single locality actually contains information on the spatial heterogeneity of the landscape (Pickett and Cadenasso, 1995) of this Early Permian time in the Wuda region.

Further studies of the locality are planned and will yield additional information on many details of this very special fossil lagerstätte that has allowed us to see three peat/coal-forming floras as adpression floras.

Acknowledgments

We dedicate this paper to Aureal Cross who inspired many geologists and paleobotanists with his synthetic view of coal formation and its relationship to other biologic and geologic processes. We would like to thank Shen Guanglong and Feng Zhuo, Northwest University in Xi'an, Shaanxi, Wu Xiuyuan of Nanjing Institute of Geology and Palaeontology, and Barbara Pfefferkorn for their help during field research. The dean of paleobotany in China, Li Xingxue, Susan Gill, Robert Giegengack, and others in both departments helped in many ways. This project is being supported by grants from the National Natural Science Foundation of China (Projects No. 40572008, 40102002 and 40321202) and the Chinese Academy of Sciences (Project No. KZCX2-SW-130) to J. W., and a grant from the Research Foundation of the University of Pennsylvania to H.W.P.

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Figures

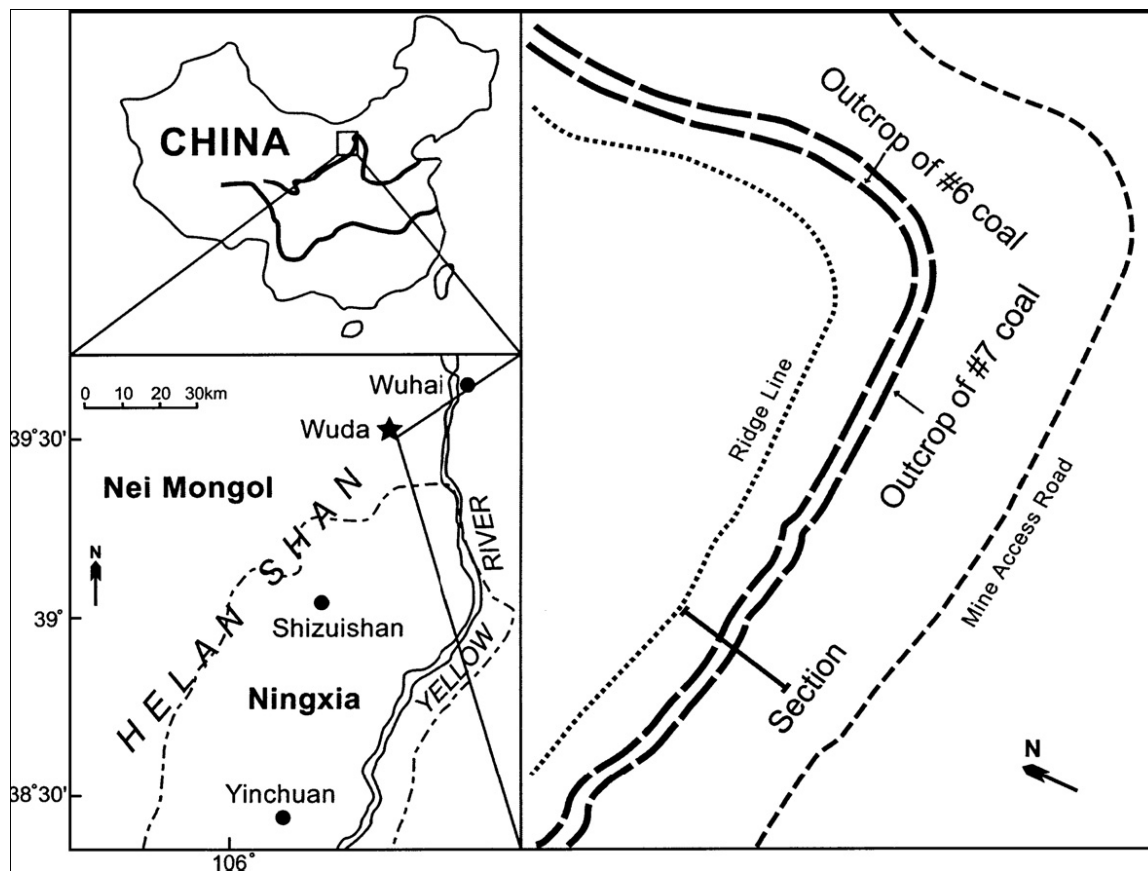


Fig. 1. Location of the locality in the Wuda Coal District of the Nei Mongol Autonomous Region in northwestern China. The observations and collections were made in and near the section shown in map C.

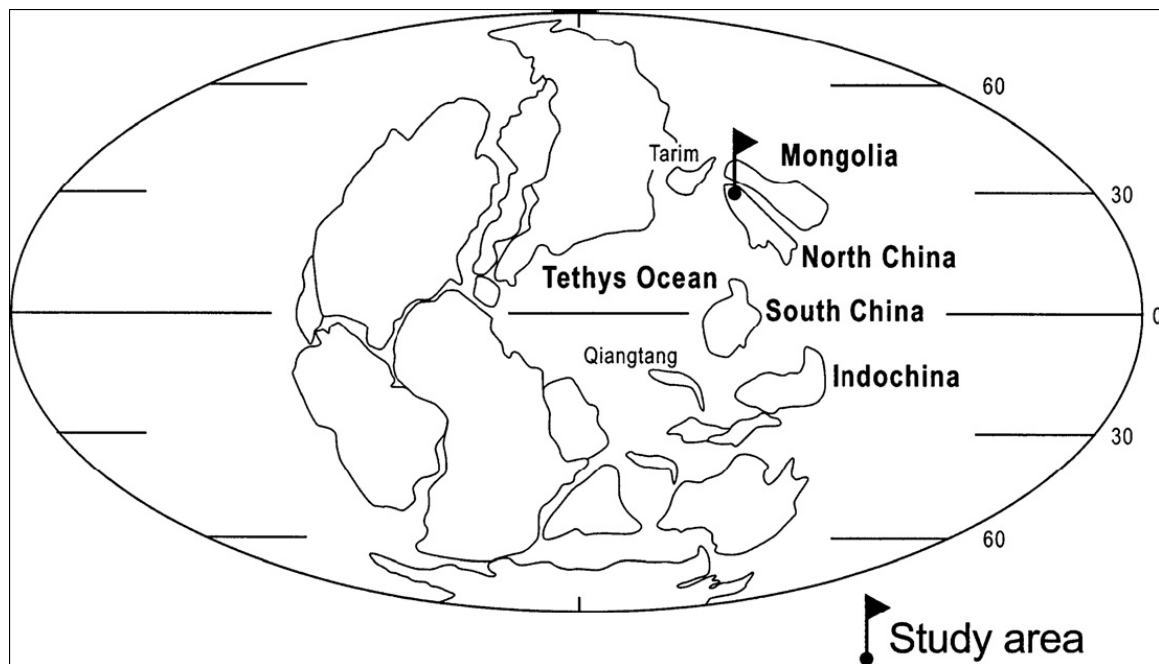


Fig. 2. Position of study area on North China Plate in Early Permian time. Map modified after Ziegler et al. (1997).

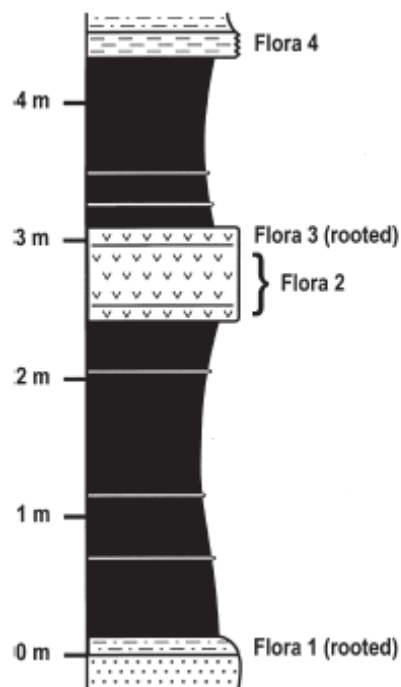


Fig. 3. Stratigraphic section through lower No. 7 and upper No. 6 Coal in Wuda Coal District. A volcanic tuff layer separates the two coal beds.

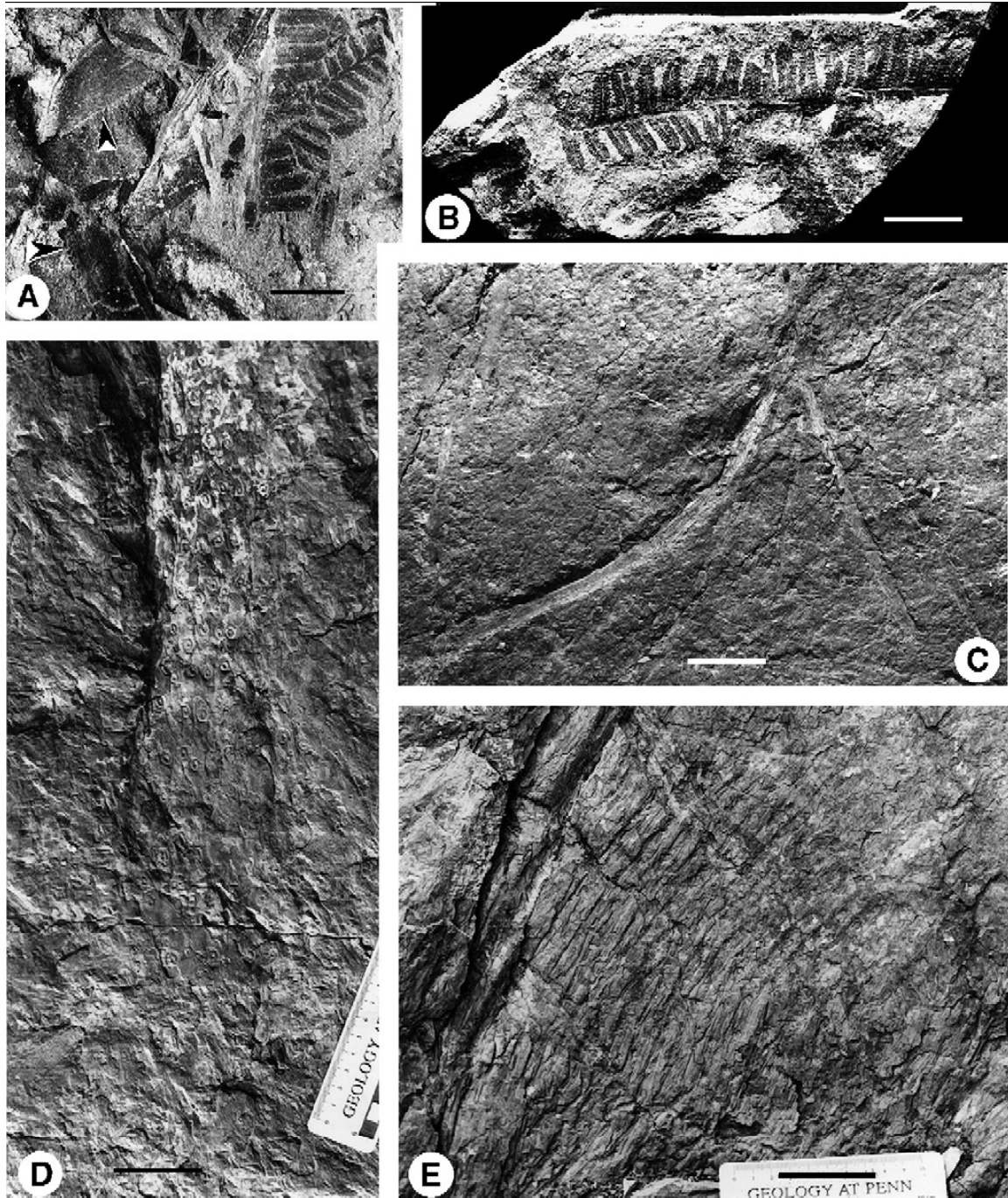


Fig. 4. Representative members of the underclay flora (flora 1). Scale bar in A, B=1 cm; C=20 cm; D, E=5 cm. (A) *Pecopteris* sp. and *Cordaites* sp. (arrows), PB 20755. (B) Fertile pinnae of *Pecopteris* sp., PB 20756. (C) Pteridosperms (?) stem. (D) *S. ficoides*. (E) Lycopsid stem.

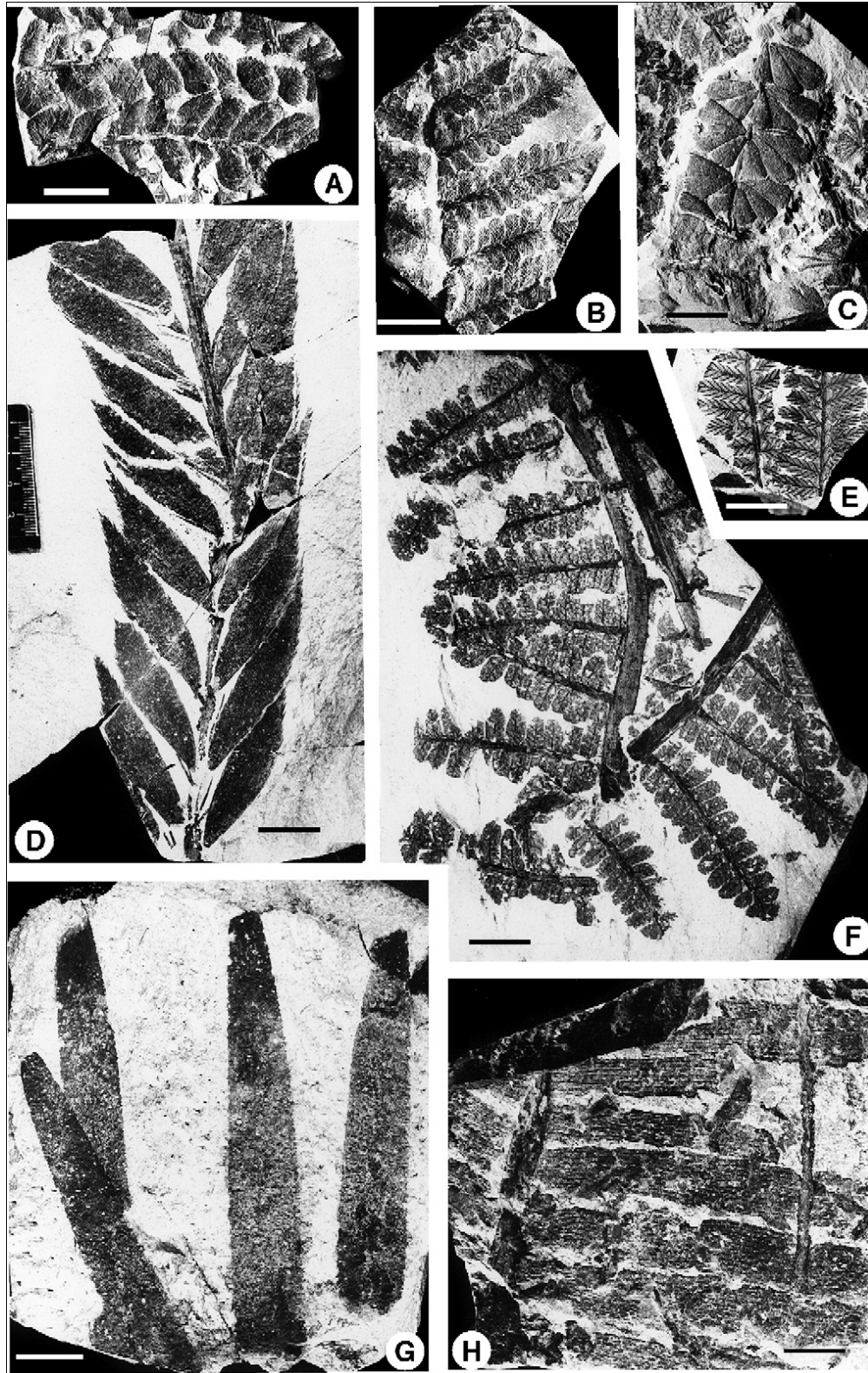


Fig. 5. Representative members of the lower and middle tuff layer flora (flora 2). Scale bar=1 cm with the exception of D and G where they are 2 cm. (A) *Pecopteris lativenosa* Halle, PB 20757. (B) *Pecopteris* sp., PB 20758. (C) *Sphenophyllum speciosum* (Royle) McCl., PB 20759. (D) *Paratingia* sp., PB 20760. (E) *N. feminaeformis* (Schloth.) Sterz., PB 20761. (F) *Pecopteris hemitelioides* Brongn., PB 20762. (G) *Cordaites* sp., PB 20763. (H) *Pterophyllum daihoense* Kaw., PB 20764.

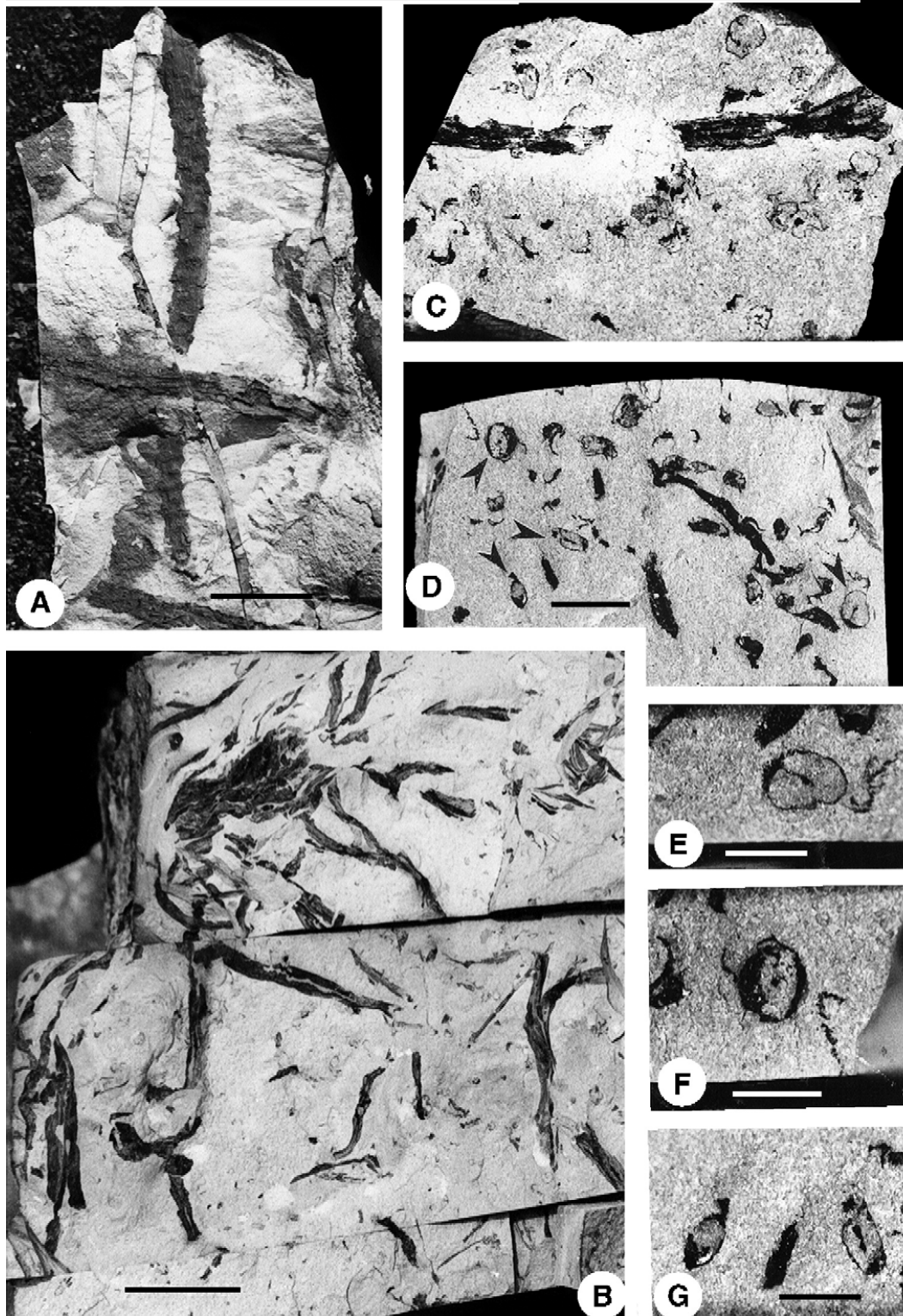


Fig. 6. Representative members of the upper tuff layer flora (flora 3). Scale bar in A=5 cm; B=3 cm; C, D=1 cm; E, F, G=2 cm. (A) Axis of uncertain affinity, PB 20765 (B) *Stigmaria* sp. with appendices (rootlets), PB 20766. (C–D) Rootlets preserved in situ in various orientations, PB 20767 and PB 20768. Arrows show the positions of cross sections enlarged in the following figures E–G. (E–G) Magnified cross sections of Stigmarian rootlets from D showing the vascular bundle and its attachment to the outer wall through a band of tissue.

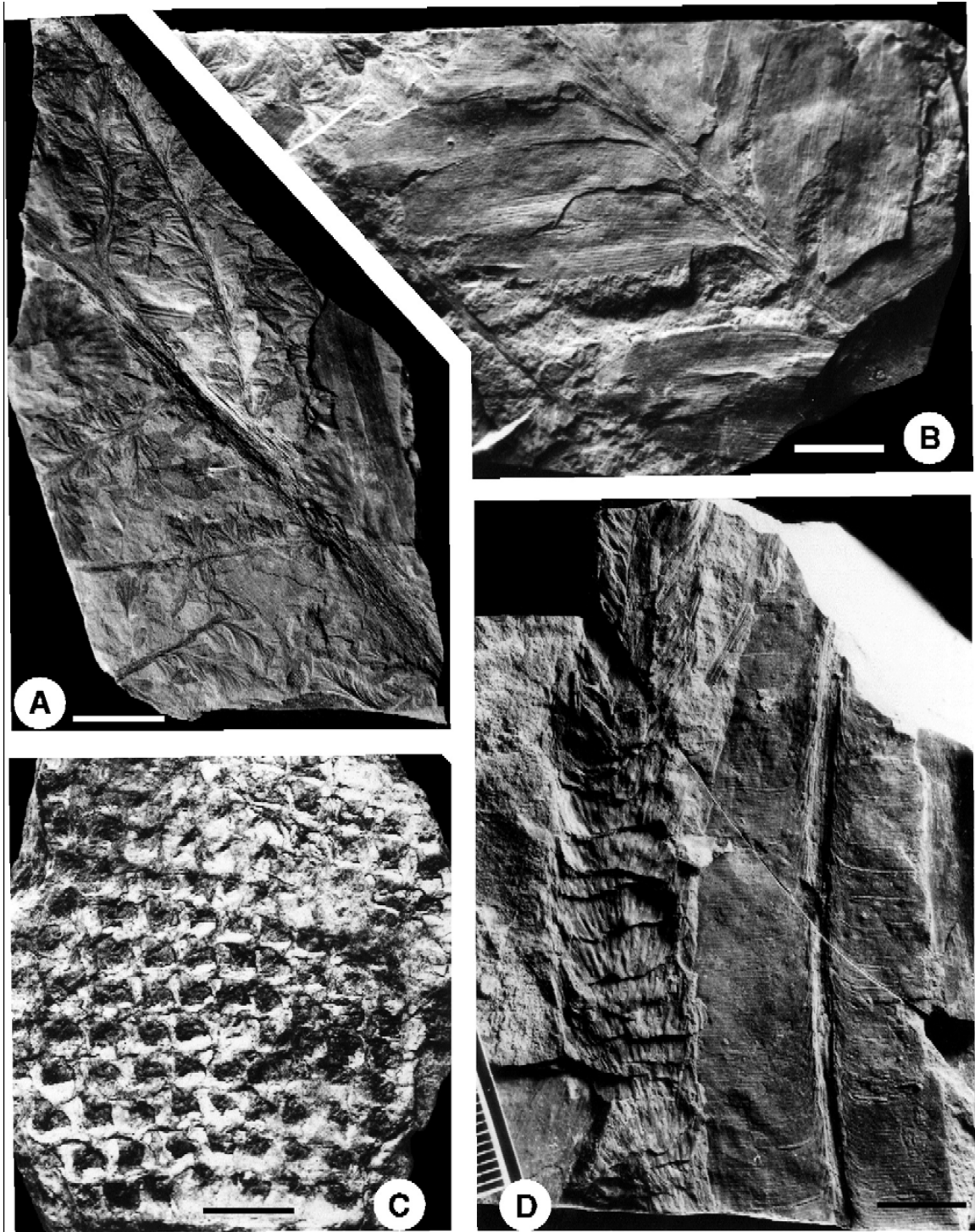


Fig. 7. Representative members of the Roof Shale flora of No. 6 Coal (flora 4). Scale bar=1 cm. (A) *Callipteris* (s.l.) sp., PB 20769. (B) *Yuania* sp., PB 20770. (C) *Lepidodendron* (s.l.) sp., PB 20771. (D) *Discinities* sp. (left) and *Taeniopteris multinervis* Weiss (right), PB 20772.

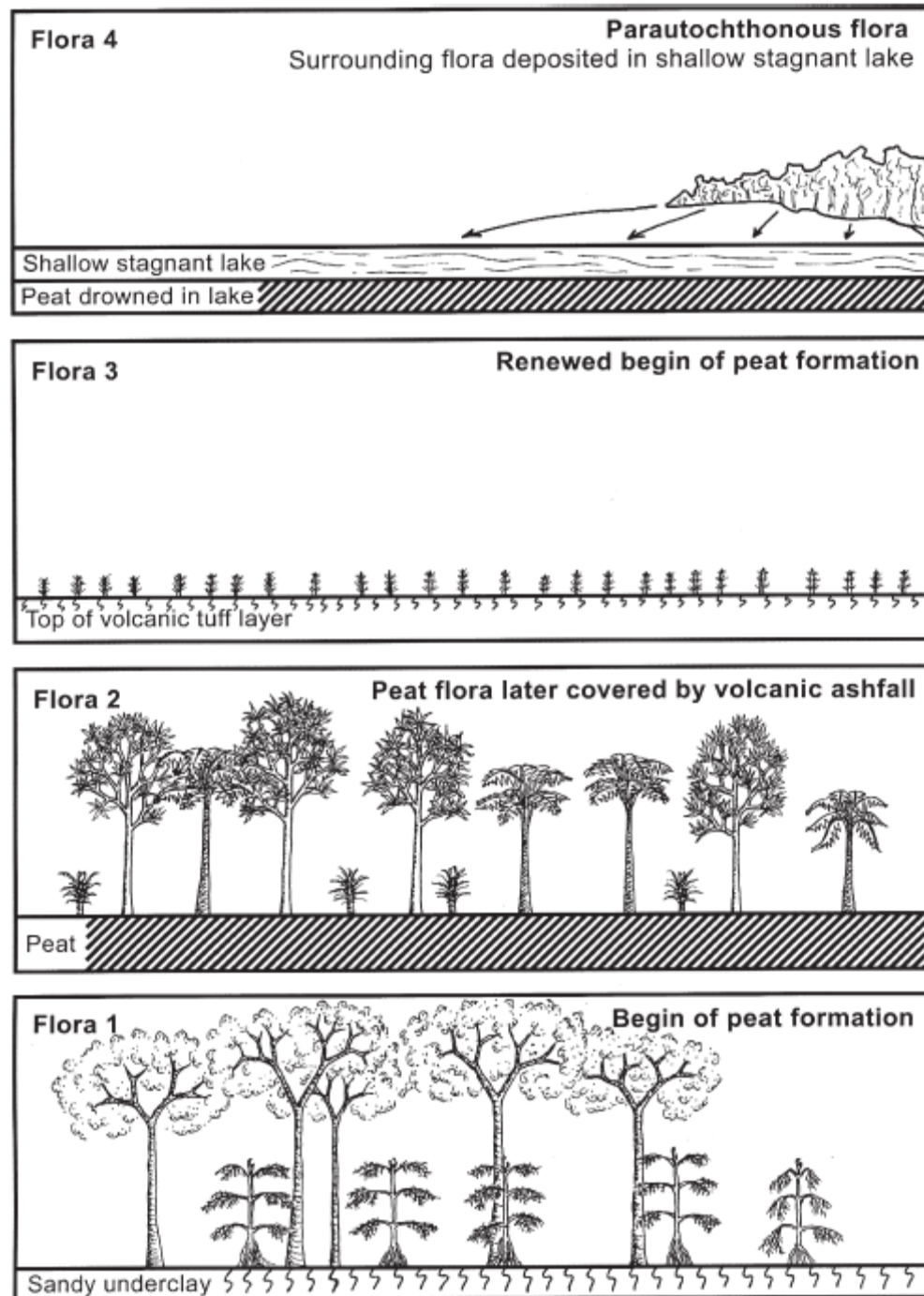


Fig. 8. Reconstruction of the four floras and landscapes preserved in the Wuda locality in Inner Mongolia in time sequence from oldest (flora 1, bottom) to youngest (flora 4, top). Flora 1 consisting of lycopsids, pteridosperms, and ferns (not shown in reconstruction) growing on a sandy soil preserved in situ. Flora 2 consisting of *Cordaites* trees, tree ferns, and smaller *Paratingia* growing on peat, that later became the No. 7 Coal. This flora is preserved autochthonously in the ash-fall tuff. Flora 3 growing as a pioneer vegetation on the ash-fall consists only of one species of small lycopsid with a stigmairian root system. Flora 4 consisting mostly of *Taeniopteris*, a callipterid (s.l.), *Noeggerathiales*, and one species of lycopsid growing around a shallow lake, the flora being preserved parautochthonously in the lake sediments that form the roof shale of the coal. There is no indication of a significant hiatus and the time represented by the entire section is geologically speaking probably relatively short.